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Blue shift of electroluminescence in AlGaAsSb/InGaAsSb double heterostructures with asymmetric band offset confinements

M. P. Mikhailova, B. E. Zhurtanov, K. D. Moiseev, G. G. Zegrya, O. V. Andreychuk, T. I. Voronina and Yu. P. Yakovlev
Ioffe Physico-Technical Institute, RAS, 194021, St.Petersburg, Russia

Lately there has been intensive research in mid-infrared III–V semiconductor diode lasers emitting from 3 to 5 μm. An important application of these lasers is ecological monitoring and tunable diode laser spectroscopy. Sb-based lasers operating at up to 180–200 K in pulsed mode and 110–120 K in cw mode were realized [1, 2]. Novel type II laser structures using an intersubband transitions were demonstrated [3, 4]. Main physical processes limiting operation temperature of the longwavelength lasers are non-radiative Auger recombination, intervalence band absorption, carrier heating as well as current leakage due to poor electron and hole confinement. Attempts were made to improve electron and hole confinement by using MBE grown laser structures with high Al-content cladding layers [5]. Further progress in improving mid-infrared laser performances is connected with new physical approaches to laser structure desing optimization.

We report here the first results on creation and electroluminescence (EL) study of AlGaAsSb/InGaAsSb double heterostructures (DH) with high Al-content (64%) confined layers ($E_G = 1.474$ eV) and a narrow-gap active layer ($E_G = 0.326$ eV) grown by LPE method. Two kinds of diode laser structures were fabricated on N- and P-GaSb substrates, below we will be referring to them as structure A and structure B respectively (Fig. 1). These structures consisted of the following layers: structure A N-GaSb/N-$Al_{0.64}Ga_{0.36}AsSb$/n-$In_{0.94}Ga_{0.06}As_{0.82}Sb_{0.18}$/P-$Al_{0.64}Ga_{0.36}AsSb$/P-GaSb and structure B had inverted sequence of the layers of the same compositions of quaternary solid solutions, P-GaSb/P-$Al_{0.64}Ga_{0.36}AsSb$/p-$In_{0.94}Ga_{0.06}As_{0.82}Sb_{0.18}$/N-$Al_{0.64}Ga_{0.36}AsSb$/N-GaSb The N- and P-type layers of the AlGaAsSb solid solutions were obtained by Te and Ge doping, respectively. The narrow-gap active layer of the n-InGaAsSb was undoped and the p-InGaAsSb layer was doped by Zn to 1×10^{17} cm^{-3}. The thickness of the confined layers was as high as 2 μm, and the active layer thickness was in the range 0.4–1.4 μm.

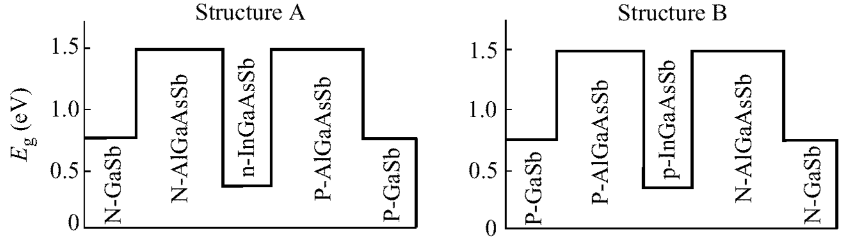

Fig 1. Energy band profiles of laser structures A and B.

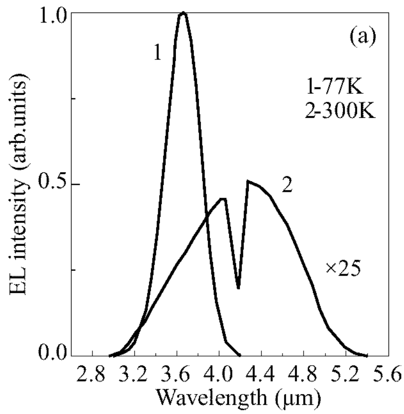

Fig 2. Electroluminescence spectra of the N-AlGaAsSb/n-InGaAsSb/P-AlGaAsSb (a) and P-AlGaAsSb/p-InGaAsSb/N-AlGaAsSb (b).

The main problem of the LPE growth of the InAs-rich narrow-gap solid solutions lattice-matched to GaSb and wide-gap AlGaAsSb is a big difference in the values of the thermoconductivity and thermal expansion coefficients of these materials. To solve this problem we used a special thermodynamic calculation of equilibrium phase diagrams of the quaternary solid solutions and an original growth technique. High quality lattice-matched epilayers were grown onto GaSb (100) substrate by liquid phase epitaxy using a horizontal graphite multiwell sliding boat. The temperature of epitaxy was about 600 °C. The lattice mismatch of the $Al_{0.64}$GaAsSb epitaxial layers as low as 0.05% was obtained. The lattice mismatch of the $In_{0.94}$GaAsSb epitaxial layers was about of 0.3% at room temperature.

Mesa-stripe laser structures with stripe widths 11–45 μm and the cavity length 300 μm were fabricated by standard photolithography. EL spectra were measured using MDR-4 grating monochromator and a lock-in amplifier. The emission signal was registered by liquid N2-cooled InSb photodetector. We studied spectra of spontaneous emission and emission intensity versus drive current at 77 and 300 K under quasi steady-state. Spectra of coherent emission in pulsed mode were studied at $T = 80-150$ K, as well as temperature dependence of the threshold current. In laser structures A spontaneous emission was obtained at $\lambda = 3.8$ μm ($h\nu = 326$ meV) at $T = 77$ K and $\lambda = 4.25$ μm ($h\nu = 291$ meV) at room temperature which corresponds to energy gap of the InGaAsSb active layer. The emission band had a Gaussian symmetric shape. Full width at half maximum (FWHM) of the emission band was 34 meV (77 K) and increased up to 90–115 meV at 300 K (Fig. 2a). The emission intensity varied linearly with drive current and decreased by a factor of 30 as temperature was raised from $T = 77$ K to 300 K. Lasing with single dominant mode at $\lambda = 3.776$ μm ($T = 80$ K) was achieved. Threshold current as low as $\sim$ 60 mA and the characteristic temperature $T_0 = 26$ K in the temperature range 80–120 K were observed.

In turn, in structures B an intensive spontaneous emission and superluminescence were only obtained. Electroluminescence with very narrow asymmetric bands (FWHM $= 7-10$ meV at 77 K and 30 meV at 300 K) was observed (Fig. 2b).

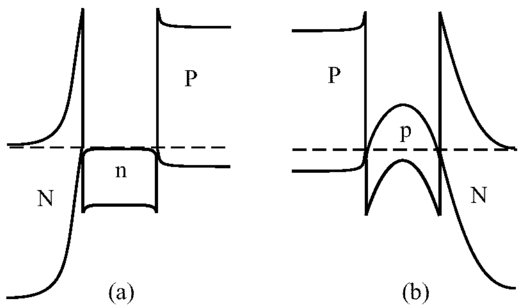

Fig 3. Energy band diagrams of laser structures A and B with high asymmetric band offset confinement.

A blue shift of the emission band maximum of up to 60–70 meV was found relative to the emission band maximum in structures A. EL was peaking at photon energies $h\nu = 380-402$ meV ($\lambda = 3.08-3.26$ μm). It is interesting to note that in B-structures the emission wavelength does not practically change in a wide range of drive current (50–170 mA) and them sligthly increases with further current rising.

To explain the obtained experimental results we examined the energy band diagrams of both laser structures. We found that in our case the $Al_{0.64}Ga_{0.36}AsSb/In_{0.94}Ga_{0.06}AsSb$ heterojunction was close to broken gap at $T = 300$ K with zero energy gap between the valence band of wide-gap semiconductor and the conduction band of the narrow-gap active layer. Such systems behave as semimetals with ohmic current-voltage characteristics at room temperature [6]. Band energy diagrams of the DH laser structures had strongly asymmetric band offsets: $\Delta E_C = 1.46$ eV and $\Delta E_V = 0.31$ eV (Fig. 3).

We explain the observed strong dissimilarity of EL spectra in structures A and B by their being due to different radiative recombination transitions. It was found in structures A the radiative recombination occurs in the active layer and corresponds to band-to-band recombination ($h\nu = 326$ meV at $T = 77$ K) (Fig. 3a). In these laser structures we used N- and P-AlGaAsSb cladding layers doped in excess of 8×10^{17} cm^{-3} which improved the hole and electron confinements and reduced the built-in serial resistance of the confining layers.

In turn, in structures B there were used lightly doped ($1-5 \times 10^{17}$ cm^{-3}) P-AlGaAsSb confined layers. We suppose that in these structures the radiative recombination transitions occur near the P-AlGaAsSb/p-InGaAsSb interface (Fig. 3b). This is supported also by electron beam induced current measurements. The observed intensive EL and blue shift of the emission band maximum relative to the emission band maximum in structures A can be satisfactorily explained by indirect (tunnel) optical transitions of localized electrons and holes from the quantum well levels across the p-p heterointerface (Fig. 4). In this case a two-dimensional electron gas can form in the quantum wells near the interface on the side of InGaAsSb solid solution due to electron resonant transfer from deep acceptor levels situated in the lightly doped wide-gap AlGaAsSb layer ($E_A = 400$ meV, a native defect $V_{Al}Sb_{Al}$) [7]) to the conduction band of the narrow-gap InGaAsSb one. Thereupon, under applied bias the tunnel radiative recombination leads to appearance of the narrow emission bands with photon energy $h\nu = 0.37-0.40$ eV which will be different from the energy band gap of the narrow-

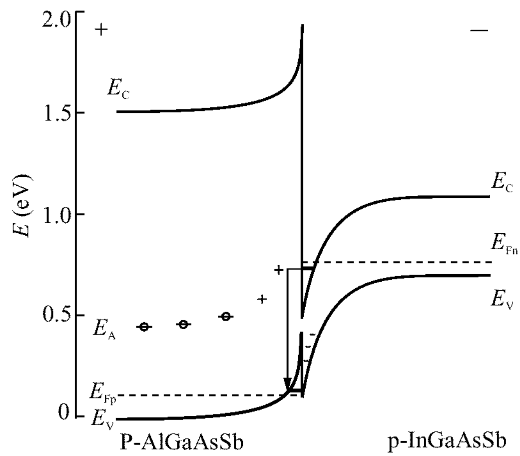

Fig 4. Energy band diagram of the type II P-AlGaAsSb/p-InGaAsSb heterojunction under applied bias.

gap semiconductor ($E_G = 0.326$ eV) and exceeding it. It is evident in this case the EL emission wavelength must not depend on applied bias as far as a lattice heating contribution is not substantial and we observed it really in the experiment. A similar "blue" shift was observed recently by us in DH laser structures with confined layers contenting Al of 34% in solid solution [8].

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